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ECOLOGY

GEOSITUATIONAL MODELLING OF COASTAL MARINE SYSTEMS

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The article summarizes years of experience of geographical situation modelling of coastal marine systems in the Baltic Sea region and adjacent territories. Kaliningrad universities and academic institutions have done extensive research on the diversity of approaches and models of the regional geographical situations as well as on identifying the most promising coastal marine areas. Some of the models presented in the present paper are qualitative, while others are empirical and statistical ones. However, the majority of the models can be referred to as forms of graphic and image mapping. The significance of the regional models lies in their specificity, a more detailed character (compared to the generalist ones) and the possibility of using them to back up managerial decisions in critical and emergency situations in order to minimize the negative effects of natural (storms, floods, earthquakes, etc.) and anthropogenic emergency situations. The authors developed a matrix classification attributable to a particular class of models for the situations leading to uncertain outcomes. The authors suggest using numerical methods combined with the empirical and statistical models for the assessment of the impact of industrial fishing on marine environment, minimizing the consequences of storms, floods and others factors. Special attention is paid to the modelling of climate change and geo-ecological consequences, as well as to atlas mapping and landscape planning. As a result of the geographical situation analysis the authors got new insights into the solar-terrestrial links, marine-terrestrial ecosystems, global and regional processes related to climate change, oceanisation, the vulnerability of natural systems under the increasing pressure of anthropogenic activities, and continuously increasing risks presented by industrial agriculture and other types of land use.

Key words: geographical situation modelling, coastal marine systems, Kaliningrad region, types of models, practical significance, prospects of development

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Introduction

In the late 1960s, the need to model natural and social cataclysms and construct global and regional development scenarios amid increasing environmental, geopolitical, and socioeconomic problems encouraged leading international scientists to support the initiative of the Italian industrialist and philanthropist Aurelio Peccei. As a result, the Club of Rome, which is familiar to many, was established. Since then, many forecasts for the future of the humanity have been grim. The main cause of it is underestimating environmental, demographic, and social problems.

Modelling geoecological situations of varying degree of danger in coastal and marine systems was focused until recently on storms and floods. However, the development of marine transportation, offshore drilling and extraction, industrial fishing, tourism, and other types of human impact on geosystems have given a new perspective on the problem. Today, models and modelling cover a widening range of regional environmental issues [5; 10; 18, etc.]. The authors of overviewed publications estimate these problems differently. However, all assessments are brought together by a systemic approach to geographical situation analysis, which takes into account natural, social, and technological factors. Dissatisfaction with global modelling calls for a search for the most promising regional studies within one of the most rapidly developing areas — modelling regional geographical situations. Many researchers — including the authors of this work — believe that it plays an increasingly important role in optimising nature management and preventing dangerous geographical and demographic situations, as well pandemics and many other natural and human-induced phenomena [13]. This holds especially true for coastal regions, which are characterised by high geoecological sensitivity.

In Russia, world dynamics models [19] are often coupled with regional assessments. This makes development scenarios more precise and concrete. Such forecasts focus on fishing, agriculture, energy, and other industries. The most complex variation is multi-factor models, which take into account interconnections between forces that are external to the system. Such geographical situations occur in land/ocean, ocean/land, and land/ocean/atmosphere systems. However, they become even more complex if solar/terrestrial relations, human impact, and other factors are taken into account. The attempts to construct purely numerical — physical and mathematical — models of regional geographical situations have not been very impressive. Thus, they were supplemented with the improvement of empirical and statistical modelling methods [5; 11; 18] and intersystem and interdisciplinary approaches to analysing critical geographical situations (types of storms, floods, draughts, earthquakes, etc.).

This work is an overview of the results of geographical situation modelling in the coast/sea system of the Baltic regions and other parts of the World Ocean. Kaliningrad geographers, geoecologists, and oceanologists — members of marine and terrestrial expeditions, have obtained these results over the last 25—30 years. Some of these models are of verbal or qualitative nature [4; 5] and others are numerical ones [11; 14]. However, most of them are models of cartographic geographical situations [3; 7; 8] arising in local and mesoscale space-time continua. Among them, one can distinguish models of conflict, critical, and catastrophic geographical situations with acceptable and unacceptable risks to economic and other activities in river mouths and lagoons and on open marine coasts. Matrix classifications — which are categorised as models themselves — have been developed to handle situations with a high degree of geoecological consequence uncertainty.

Mapping and calculations are often carried out separately, since maps do not reflect changes in time and numerical models lack spatial referencing. However, combining geographical and physical/mathematical models makes it possible to carry out comprehensive studies of geographical situation dynamics [9]. The multivariance of situation assessments determines the sequences (algorithms) of operations in producing thematic maps and mathematical processing of data [7].

The overview starts with regional models taking into account the solar/terrestrial relations in changing climatic geographical situations, storm surges, currents, and seacoast destructions. Kaliningrad researchers focus on the modelling of climate changes and the geoecological consequences, coast destruction, and sand dune flooding on the Curonian Spit [20; 22; 23]. A number of geological/geophysical and geological/geochemical models reveal the connections between surface phenomena and endogenous processes — gas-driven and gas-hydrothermal volcanism and seismicity [8].

Empirical and statistical predictive models for the fishing industry in the Peruvian upwelling and krill yield estimation present a good example of novel and practice-oriented research on the Antarctic waters [2; 21]. A multi-criterion approach to evaluation models of natural landscape sensitivity [6; 7] often initiates heated discussion. However, the Kaliningrad case shows that this approach has an increasing number of supporters.

Atlas mapping and modelling are another promising area of geographical situation analysis. Researchers take a step from isolated maps to a comprehensive analysis of a wide spectrum of geographical situations, which sometimes interact, sometimes clash, and always require administrative decisions. In this respect, landscape planning is the most promising area [3; 13].

Climate modelling and changes in solar activity

In the absence of a linear connection between the temperature of near-surface atmosphere and geographical situations in the Polar Regions (melting of glaciers and an increase in their area), predictive scenarios can differ significantly. However, the higher the solar activity the warmer the climate — this thesis has been corroborated by hundreds of years of observations. The level of solar activity in even-numbered centuries is higher than in uneven-numbered ones. Moreover, there are varying-length periods of extremely high solar activity. Fluctuations in the average air temperature correlate not only with the Wolf number but also with the fluctuations in the average length of 11-year solar activity cycles. Century cycles in climate change are interlinked with the relevant fluctuation in solar luminosity and pulsation.

The analysis of multi-year data on average air temperature in the city of Kaliningrad has not shown any significant increase in this parameter. The largest amplitudes are associated with 1.5—2-year and 9—11-year cycles, which suggests a cause-effect relation between the solar activity and the Earth's climate [6].

In view of the extremely high solar activity in the 20th century — the highest in the past 400 years — storm surges became more frequent on the coast of the Baltic Sea. Another recurrent phenomenon is severe draughts in Europe, which are observed every 35—37 years.

Estimated P (relative frequency) and Δp (standard deviation) of storm surges in the delta area of the River Pregolya

Period	Level, cm					
	95		155		180	
	P	± Δp	P	± Δp	P	± Δp
1950—1969	0.4	0.11	0.05	0.05	—	—
1970—1989	0.7	0.1	0.1	0.07	0.05	0.05
1990—2009	0.6	0.11	0.2	0.09	0.05	0.05
1950—2009	0.6	0.06	0.1	0.04	0.03	0.02

Source: [15].

In the models of storm surges in the delta of the River Pregolya (Kaliningrad), the 16—18-year cyclicity agrees with the empirical data and leads to a conclusion that extremely severe floods can be expected in 2016—2018. The period of repetition of severed floods along the Rhine (based on 674—1995 observation data) is 110—112 years, which corresponds to the century solar activity cycle [7; 25].

Modelling links between the solar activity/climate/ecosystem makes it possible to build a long-term climate change scenario for the South-East Baltic [6,7]. Imitation modelling helped to identify possible geoecological consequences — the average temperature of near-surface air may increase by 1—5 °C by 2040. However, in view of the fact that the average temperature did not change in 1848—1989, it will increase by the mid-21st century by only 2°C. The forecasted increase in annual precipitation will reach 100 mm/year [23; 24].

The numerical simulation of models demonstrated quasiperiodic variations in all components of the climate system and their adaptation to the conditions of the Kaliningrad region. Temperature changes occur in counterphase with precipitation (maximum temperature coincides with minimum precipitation). The ecosystem is more sensitive to humidity than temperature. A linear approximation of the climate change trend produced a different result — since the mid-1970s, the average air temperature has increased by 0.43 °C/10 years in the Russian Federation, which is 3.5 times the global level. The positive trend in total precipitation has reached 0.8 mm/month/10 years over the same period. However, the area of snow cover has been diminishing annually. The frequency of extreme winter and summer climate phenomena — storms, floods, draughts, and wildfires — has increased [20; 25; 26].

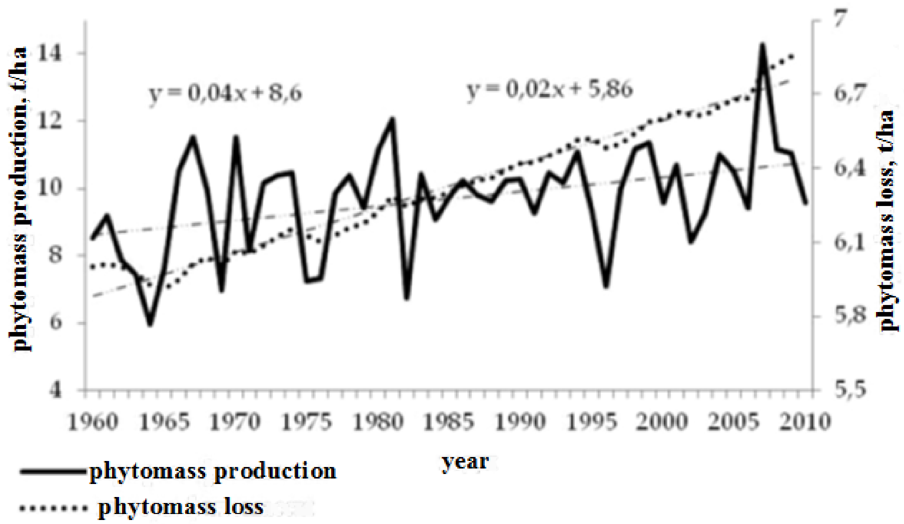

Fig. 1. Annual course of and linear trends in phytomass production and loss, based on leaf and wood litter data

Source: [7].

An empirical and statistical model demonstrates quasiperiodic fluctuations in the measured parameters, and helps to identify characteristic periods of rises and falls in forest productivity in the Kaliningrad region.

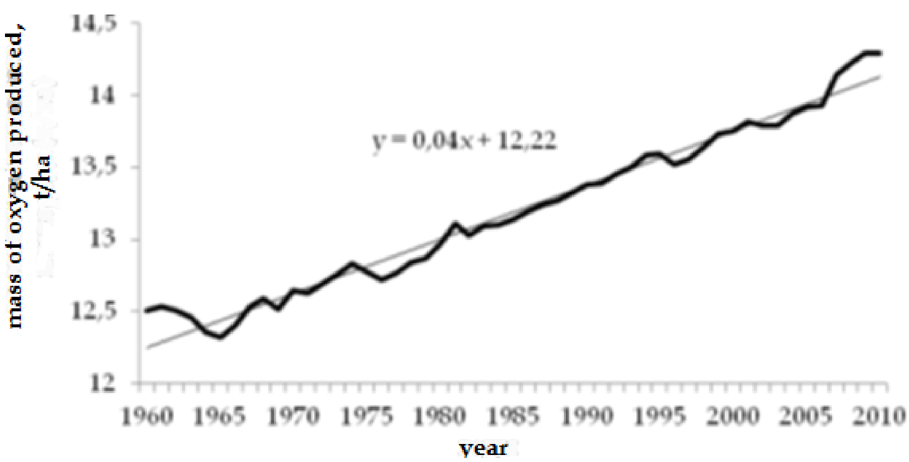

Fig. 2. Annual course of oxygen production by a mixed forest

Source: [7].

An important result of modelling for recreational impact planning is a positive trend in the oxygenation of the near-surface atmosphere in the Kaliningrad region. In the case of agriculture, negative consequences can be associated with phenophase asynchrony and bees flying out for pollination. An increase in rainfall intensity leads to significant losses in grain crop yield. The mass reproduction of ticks increases the risk of infections in humans [23; 24].

Water cycle and oceanisation models

M.I. Lvovich's classical model describes the process of ocean water evaporation through channel runoff and precipitation. It is expressed in the following formula:

$$E = P + R,$$

where E is evaporation; P — precipitation, and R — river runoff.

Based on many years' research into ocean dynamics, V.V. Orlenok developed a fundamentally new model. It is based on the following water balance equation:

$$P + R + T - E - F = N, N > 0,$$

where T stands for the arrival of intraplanetary water; and F — for water irreversibly lost to photolysis. There is no zero balance in the hydrosphere. According to Orlenok, arrival exceeds losses, which contradicts V.I. Vernadksy's postulate of constant volume of water on the planet. Instead, the author proposes a model of global oceanisation (an equivalent of the 'great deluge'). Not all oceanologists agree with the model. However, there are many facts to support it — the prevalence of ocean floor depressions over elevations, Venice's continuing flooding, and the need for flood control in the Netherlands, Germany, and along the Baltic coast, etc.

Despite the global nature of the above models, they can be tested only at a regional level due to differences in planetary and hydrometeorological factors. The level of the Baltic Sea varies around its perimeter. There are also temporal changes. In 1823, the Baltic Sea level fell by 250 mm and, in 1920 and 1952 rose by 150 mm. However, there is a persistent trend — the Baltic Sea level rises at a rate of 1.5 mm/a.

The rate of the World Ocean floor subsidence shows an exponential dependence. It means that, over the past 100 million years, endogenous water has been flowing into seas and oceans at a rate of 0.6 mm/a. The total inflow of water from the subsoil is estimated by Prof. Orlenok at 37 km^3/a and losses to photolysis at 7.2 km^3/a [16; 17].

Up to 4—5 % of water is contained in the volcanic lava and ashes, which are regularly ejected from beneath. Moreover, calculations require taking into account the space component — fixed water in asteroids and meteorites.

In the trenches of the Baltic, gases (CH_4, N, O_2, H_2, etc.) are released from not only the bottom silts but also from greater depths, down to the crystalline basement. Gases seep to such deep levels through tectonic fissures.

Sometimes, deep layer gases are issued with water (gas hydrothermal vents). The upward flows of petroleum gases are accompanied by acoustic anomalies. Metal sulphides are sometimes found at the same sites [8].

Constant issue of juvenile waters and different gases is aggravated by large-scale offshore projects, which can cause collisions of the Earth's crust and earthquakes. Increased frequency of earthquakes in the Baltic and, in particular, the Kaliningrad region provides evidence in support of this idea (October 1303, August 1803, 1904, September 2004). A series of three earthquakes up to magnitude 5.2 — which is unusually severe for the East European Platform — occurred on September 21, 2004. The earthquake shook the whole region, causing serious damage to buildings and railways [8].

The lithodynamic model of the sea coastal zone

Lithodynamic studies [4; 5] in the South-East Baltic Sea and a comparison of the results obtained with the findings for the Caspian and other inland seas have demonstrated a strong similarity between the coast forming processes and lithodynamic situation at the test sites. This made it possible to develop a verbal 'management model' for sand shore and the shelf.

Fine-grained sands in upper lagoons — washed by the near-shore currents in the South-East Baltic and on the western coast of the Caspian Sea — cover the rock bench completely. This is in line with the major empirical pattern of the distribution of soft sediments on the beach and the shelf controlled by near-bend currents and the wave energy features. In these conditions, the beach width reaches 35—40 m. However, in the current divergence zone near capes, fine-grained areas are stretched along the coast in a narrow strip sandwiched between marine and land gravel sediments. Beaches are absent or they do not exceed 3—5 m in width, being composed of boulders and gravel.

Upper lagoons are dominated by fine-grained sand accumulation. Closer to the waterline, the content of heavy minerals in sand increases. However, it decreases rapidly towards the sea with the exception of runnels outlining the trajectory of water masses at relatively high speeds from the waterline towards the open sea.

Distribution of bottom soils, their grain sizes and mineralogical characteristics are indicative of a considerable length of rip currents moving bottom sediments to a significant depth of 10—15 m and more. At large capes and port facilities, near-shore currents rip to form isolated lithodynamic systems. The exchange of substances and energy between these systems is either complicated or impossible. In the case of a morphologically segmented shore, rip currents transport sands from the near-waterline cove zone to greater depths, which leads to the inversion distribution of bottom sediments along the transverse profile.

The vertical suspension distribution (R) over a continuous area of soft sediments is a two-layer one, characterised by a significant gradient in the near-bed layer and a gradual decrease in suspension content towards the surface. Sand areas stretching beyond the central parts of coves to significant depths outline the trajectory of rip currents, which transport suspensions to the open sea. Tests using luminescent tracers corroborate the above lithodynamic model.

An analysis of tracer movement and concentration proved the existence of zones of convergence of wave energy currents in coves, which creates conditions for the formation of rip currents. The above model describes the major process of sand transportation by rip currents from the cove waterline zone to grater depths. This process develops even in a slight or moderate sea conditions.

Biogeochemical mapping

A series of works present results of many-years' research into the biconcentration of heavy and transition metals in floor mosses [9, 23]. Based on a concentration index for Europe, a typology for the Baltic region has been developed. The most affected regions are Germany and Poland, followed by Lithuania, Latvia, Finland, and Norway, and least-affected Sweden and Estonia [9].

Atlas mapping and modelling

Geographical atlases play a special role in the system of regional mapping. They make it possible to analyse the condition of and prospects for the development of cohesive territorial units from natural, historical, socioeconomic, and geoecological perspectives. Regional atlases serve as a database for landscape planning for developing territories; they are crucial for administrative decision-making [1].

The *Geographical Atlas of the Kaliningrad Region* (2002) was the first of its kind in Russia. Its geological section included a series of landscape maps showing the condition of ecosystems and types of land use and suggesting measures to attain nature management optimisation, geoecological safety, and sustainable regional development,

In the process of mapping, past geographical situations (retrospective generalisations) and their possible changes (prospective projections) were modelled to identify spatial and temporal patterns. In the 2011 special edition of the World Atlas dedicated to the Kaliningrad region, the geographical situation analysis was organised as follows:

1) air quality;
2) human impact;
3) impact on public health.

The logical conclusion to analysing regional geographical situation is the map of nature conservation areas of the Kaliningrad region presented in the atlas. Unfortunately, in five years, it has become dated — a number of new reserves have appeared in the region and some of the older ones have lost their status.

The 1951—2000 array of hydrometeorological data on the Baltic Sea basin made it possible not only to model changes in climate fields with a one-month interval (air and water temperature, salinity, wind velocity, atmospheric pressure, and other parameters were taken into account) but also to identify the spatial and temporal changeability in view of trends and periodic components. Topographic maps published over 70 years helped to compile the recent *Atlas of Post-War Changes on the Territory of Today's Kaliningrad Region* (2016), which reflects not only the geopolitical and socioeconomic vicissitudes of the region but also geographical and environmental changes — those in the forest area, marine coast, and the river network [1].

A comparison of the first topographic images and a current digital topographic map was used as the key method for producing a map of the coastline transformation. An analysis of changes in the position of the coastline of the Baltic Sea and the Curonian and Vistula Lagoons helped to obtain quantitative characteristics of transformations along 450 km of the sea and lagoon coastline. These changes are described as 'transformations' to avoid conclusions about the complex nature of coastal processes along the regional coast (abrasion, accumulation, etc.). Metric differences in the coastline position were identified across the regional coast without analysing each fragment.

On the Sambian Peninsula, the most significant land augmentation (up to 200—400 m) was observed in its western part (from the village of Parusnoye to the village of Sinyavino), and at the mole of the cove of Pionersk and north of the moles of Baltiysk. This can be explained by the human-induced coastline transformations. A considerable reduction in the land area (up to 100 m) was observed west of the Cape Taran (village of Donskoye) and the coast between the delta of the Rivers Zabava and Aleyka (village of Kulikovo). There, the coast is high and cliffed, which suggested that the coastline transformations were natural.

Landscape planning

The verbal and cartographic modelling of geographical situation for the purposes of nature management is lent a new urgency by the need to perform cadastral surveys and produce land inventory across regions. In the Kaliningrad region, cartographic feasibility studies taking into account the condition of lands and the location of conservation areas will contribute to sustainable regional development [3].

Conclusions

The geographical situation approach can be used in modelling different changes in regional ecosystems. This overview covers the results of modelling large-scale global and regional geographical situations arising in coastal/marine system under the impact of solar radiation and climate change, geotectonic process and oceanisation, and near-shore and shelf currents transporting sediments into the depths of the ocean. Cartographic and empirical/statistical representation of geographical situations in the systems of complex atlas models and landscape planning seems to be very promising for supporting administrative decision-making. It will contribute to optimising land management, minimising storm surge damage, restoring eroded shores, combating climate anomalies, and reducing risks to agriculture, fishing, and other industries.

The overview did not consider regional geographical situations caused by the eutrophication of coastal waters, heavy metal and hydrocarbon pollution of the marine and water environment, and natural focal diseases of animals and plants. The authors are planning to write another article on these issues.

Using differential equations, the most popular balance models describe system dynamics as a combination of matter and energy transfer processes. Although they can be exploited in studying chemical element and compound circulation in the geochemistry of the soil/plant system, there are significant difficulties associated with their implementation. Such models do not take into account all experimental data. There are no algorithms for creating mathematical models based on empirical studies with precise extrapolation of past geographical situations. All this stresses the need for further improvement of the methods of geographical situation modelling and the principles behind them.

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